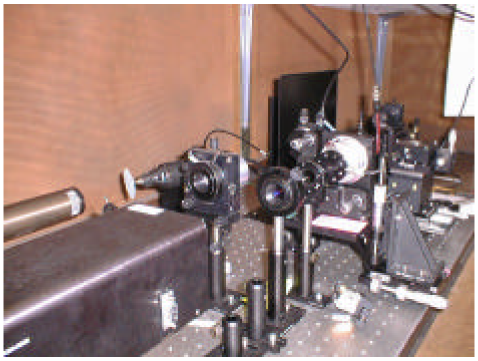

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Coherent Laser Control in an Ion-Trap Quantum Computer: Characterization of a Laser Intensity Stabilizer

ABSTRACT

One of the projects the Los Alamos Quantum Information group is currently engaged in is the development of a trapped-ion quantum computer. $^{40}Ca^{+}$ ions are trapped and laser cooled in a (linear) RF quadrupole trap until they crystallize into a "string of pearls" formation. With the ions functioning as qubits, quantum logic operations are performed via an ion addressing system; laser pulses are used to control the states of the qubits. An imaging system records the states of the ions at the end of computation.

The first component in the series of devices comprising the ion addressing system is a laser intensity stabilizer, or "noise-eater". Laser intensity stabilization is necessary for precise control of the laser pulses inducing change of ion excitation states. The noise-eater (Cambridge Research Instruments model LS-PRO) consists of a Pockels cell, liquid crystal, and output polarizer in optical series; a servo system regulates voltage drive to the Pockels cell and liquid crystal.

The noise-eater's response to input beam fluctuations, uncontrolled and controlled, was characterized. Controlled beam modulations were varied in frequency and amplitude by a function generator driving an external Pockels cell.

Plans for placing the noise-eater in an interferometer to determine whether the noise-eater produces unwanted variable phase-shifts are also discussed.

Quantum computing differs from classical computing in that it uses the quantum superposition principle to create quantum superpositions (linear combinations) of binary states. By using quantum computation on these quantum mechanical two-level systems ("qubits"), as opposed to classical computation on discrete two-level systems, certain problems can be solved more efficiently. Integer factorization, for example, can be solved in polynomial time instead of exponential time. Many classically intractable or arduous problems have very real world applications. In cryptography, encrypting keys are typically multiples of very large prime numbers, so the ability to factorize integers is relevant to code breaking.

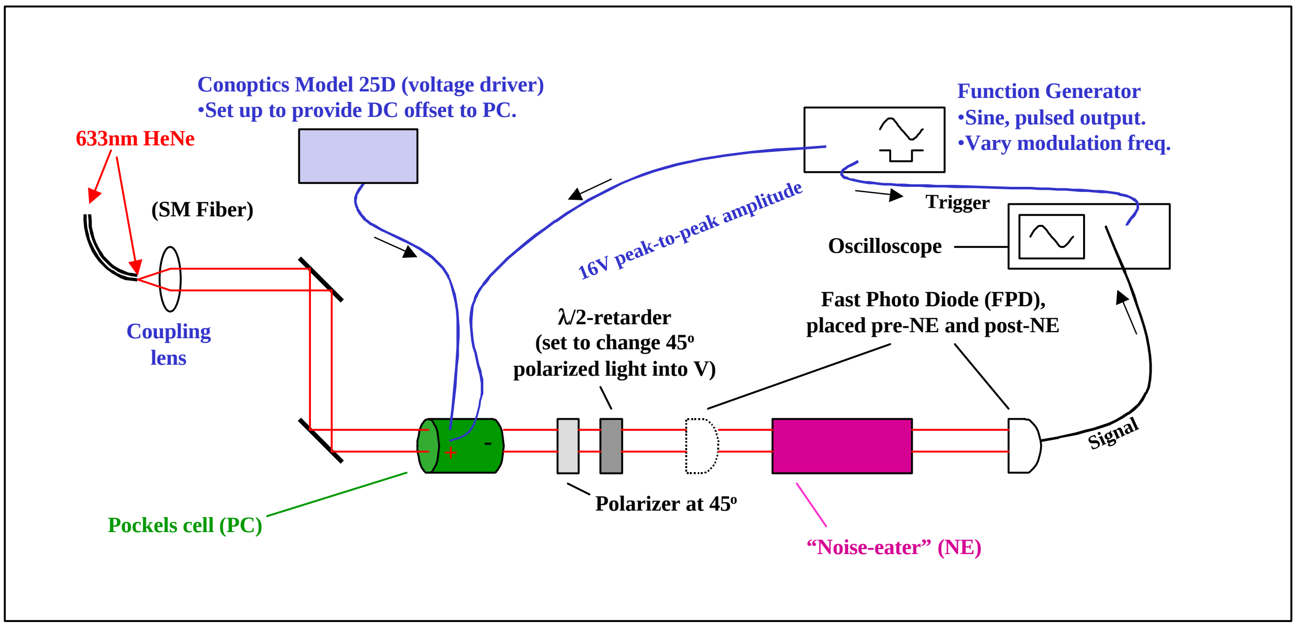
The Los Alamos Quantum information group is using trapped-ions as the physical manifestation of the qubit in its quantum computation project. The quantum computer's ion addressing system, designed by Dr. Paul Kwiat, will be used to induce state changes in individual ions via controlled laser pulses. The ion addressing system will consist of a laser intensity stabilizer ("noise-eater"), beam switch, electro-optic beam deflector, and focusing lens system. The purpose of each device, respectively, is to: stabilize the intensity of the beam for the duration of the pulse, control the duration of the pulse, change the direction of the beam towards a specific ion in the ion-trap, and precisely focus the beam onto only that ion.

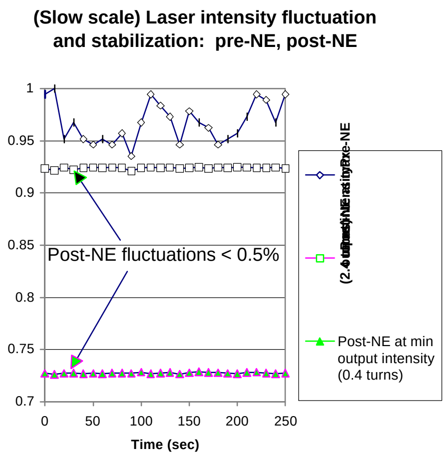
My project this semester was to characterize the noise-eater, particularly its ability to take an input beam with sinusoidally varying intensity and "flattening" it to some constant intensity. Also, the noise-eater had to be tested to determine whether the Pockels cell within introduced variable phase shifts in the light as a byproduct of flattening the input beam's intensity.

The noise-eater takes vertically polarized light as its input and sends it through a liquid crystal, Pockels cell, and vertically oriented output polarizer. The liquid crystal and Pockels cell both operate by changing the polarization of the light. This light, when transmitted through the output polarizer, becomes vertically polarized with decreased amplitude. The unit tested (Cambridge Research Instruments model LS-PRO) has an operable bandwidth of DC-2MHz. The Pockels cell removes noise above 150Hz; the liquid crystal removes low frequency noise.

The LS-PRO has a standard noise reduction ratio for each frequency in its operable bandwidth. In other words, for each modulating frequency from DC to 2MHz, the noise-eater is expected to scale down the amplitude of the intensity modulations by an amount that is the noise reduction ratio.

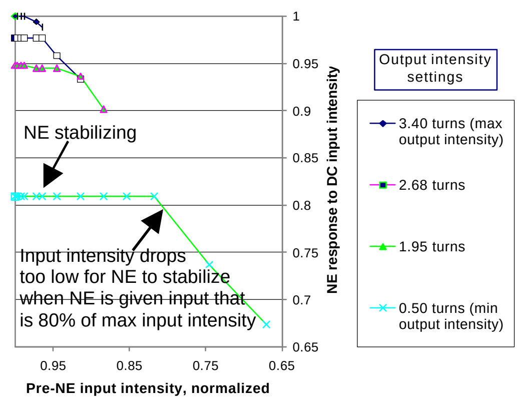
Much of the time spent on this project was devoted towards finding a suitable noisemaking source and testing setup. Initially I tried using a different electro-optic modulator than the current one, but there were difficulties providing it with enough drive voltage. A rotating hand tool with a cogged wheel, which acted like a beam chopper for DC-26kHz, modulated the intensity well; the light, however, diffracted off the edges of the cogs, sending variable spatial modes to the noise-eater. The current electro-optic modulator, a Pockels cell, was obtained and first tested with its own digital driver, which yielded square wave instead of sinusoidal modulations. Next a function generator in series with an amplifier (limited to a bandwidth of DC-20kHz) was used as a driver. Finally just the function generator was used to drive amplitude modulations with the digital driver providing DC offset. The other issue that needed to be dealt with was the electrical noise obscuring the signal from the detector. The noise was not from the detector—a fast photo diode (Thorlabs DET2-SI)—but was picked up by the BNC coax cables. The problem was first solved by using a lock-in amplifier of bandwidth DC-30kHz to isolate the detector's signal from modulations at other frequencies. An oscilloscope programmed to behave like a lock-in amplifier by using the time averaging function became the final measuring device (the oscilloscope had a broader measurable bandwidth).

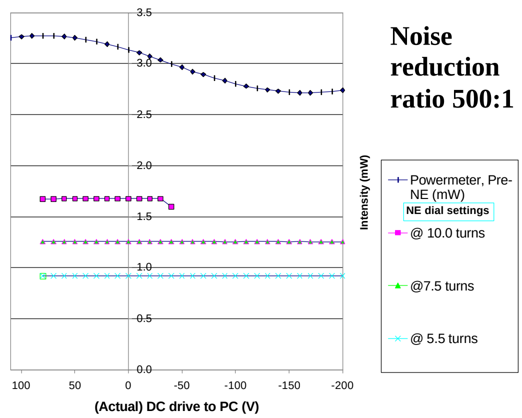


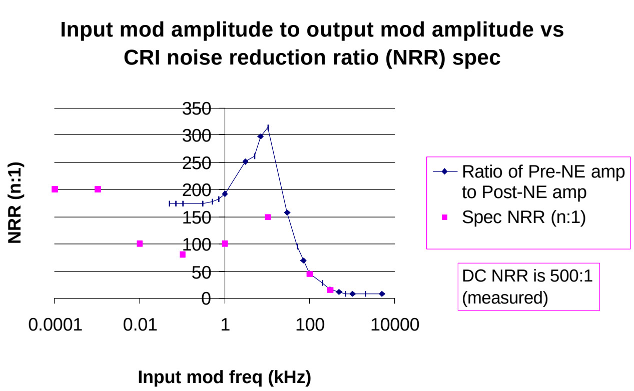


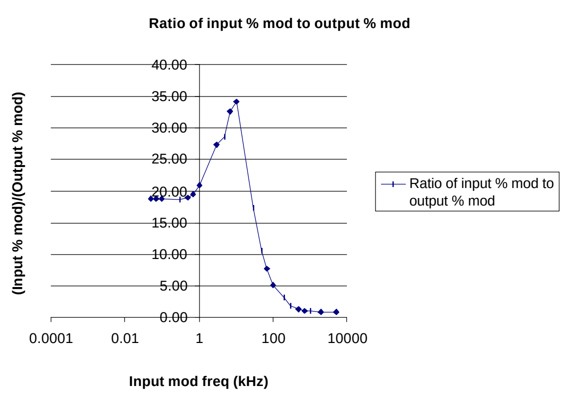
The figure at left is a measure of the noise-eater's slow time scale performance. The 633nm HeNe laser used had intensity modulations of up to ~7% of maximum intensity. The noise-eater flattened the signal to within 0.5% of maximum intensity. Including thermal drift, the signal will remain flattened to within 0.5% for 9 hours (CRI test data).

The bottom two plots are a measure of the noise-eater's response to DC input. Depending on the input beam intensity and the dial setting of the potentiometer on the noise-eater (attached to the internal servo system), the noise-eater will be able to maintain a threshold output intensity until the input intensity is decreased to X% of the maximum input intensity. Note: (# of turns allowed on 10-turn potentiometer dial/10) = max % intensity drop permissible = (100-X)%



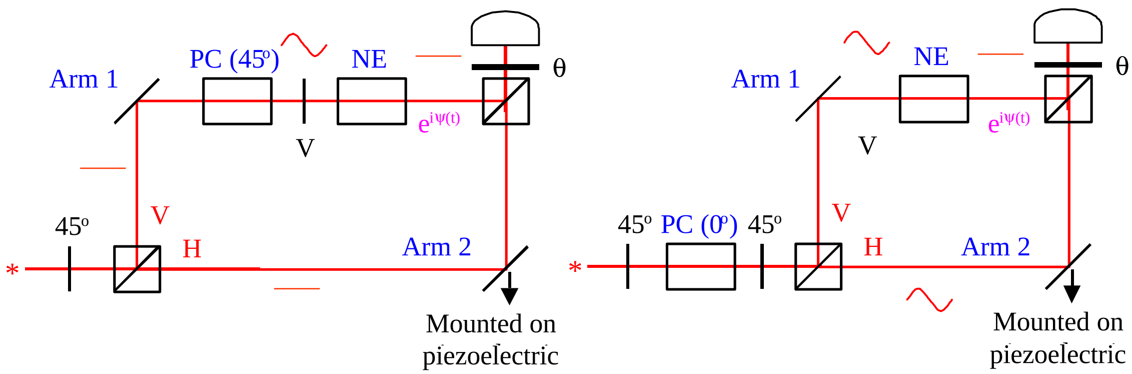






The noise-eater was given "controlled" noise—i.e., a beam with an input intensity modulating at a given frequency—generated by a tunable noisemaker, a Pockels cell between two parallel polarizers. For frequencies from 50Hz to 100 kHz the noise-eater reduced the amplitude of the modulations by scale factors better than manufacturer specifications. For 100 kHz to 2MHz, the noise-eater performed at specification. The function generator could not drive the Pockels cell at frequencies below 30Hz. Note that according to the manufacturer, in order to stabilize a 633nm laser beam, input intensity drop-offs and surges received by the noise-eater should not exceed +/-9.8% (at 442nm the noise-eater is able to stabilize drop-offs and surges of +/-13%).

The next task in testing the noise-eater is to see if it introduces variable phase shifts as the light is intensity flattened. (This has not yet been accomplished at the time of writing.) The noise-eater will be tested using a polarizing Mach-Zehnder interferometer. A polarizing Mach-Zehnder interferometer has arms with definite and mutually orthogonal linear polarizations. This is advantageous in that fewer linear polarizers are needed in the arm with the noise-eater (the noise-eater must take vertically polarized light). There are two possible testing scenarios. If the noisemaking source (the external Pockels cell) does *not* introduce a variable phase shift in the light as it changes its polarization, it is acceptable to put the Pockels cell in the same arm as the noise-eater, since the only possible phase shifting source would then be the noise-eater. Light is recombined from both arms of the interferometer and subsequently passes through a linear polarizer adjusted to equalize the transmitted amplitude contributions from each arm (the linear polarizer acts as a "quantum eraser"). The intensity seen by the detector will be flat if there are no variable phase shifts induced by the noise-eater, and changing if otherwise. If the external Pockels cell *does* introduce a variable phase shift in the light, it will be necessary to place it outside the interferometer. The intensity of the recombined light seen by the detector will be changing whether or not the noise-eater introduces phase shifts (due to the oscillating amplitude from arm #2), but the magnitude of the intensity changes will be substantially less if the noise-eater does not introduce phase shifts. For a 5% intensity modulation generated by the noisemaker in the first setup, there will be 0% intensity modulation after the noise-eater when the noise-eater does not produce variable phase shifts. If the noise-eater does produce variable phase shifts, there will be 11% output intensity modulation. For a 5% input intensity modulation in the second setup, there will be a 1% output intensity modulation when the noise-eater introduces no variable phase shift, and about a 5% output intensity modulation when otherwise.



"Noisemaker" (PC) introduces no phase shift

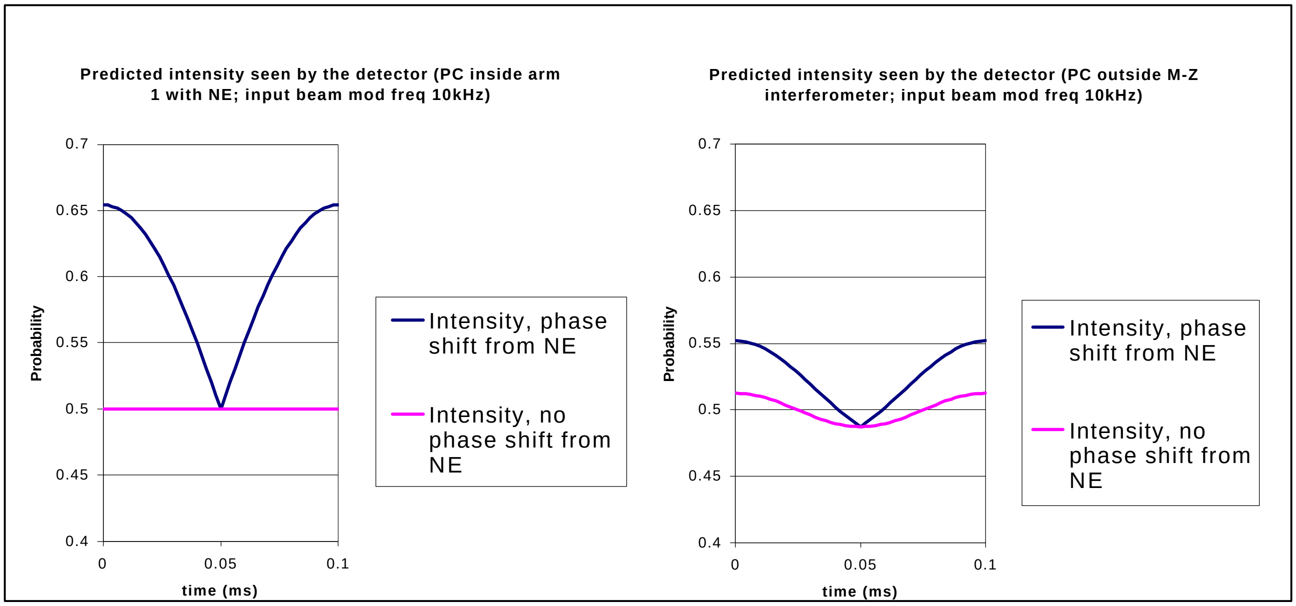
$I = \kappa^2 [1+\cos(\Delta\psi(t)/2+90^\circ)]$, κ is constant

"Noisemaker" (PC) does introduce a phase shift

$I = \underline{\kappa}^2 [\beta^2+2[1+\beta\cos(\Delta\psi(t)/2+90^\circ)]]$, where $\beta^2=W\cos(\omega t)$, $\underline{\kappa}$ is constant

ω is the (circular) frequency at which the Pockels cell is modulating the intensity. *t* is time. $\Delta\psi(t)$ is the phase-change imposed on the light in the vertically polarized arm of the interferometer by the noise-eater. The arms of the interferometer will be initially adjusted to equalize the optical path length of the two arms (including the natural birefringence of the passive noise-eater and Pockels cell, if it is placed within the interferometer). Then one arm, say arm 2, will be phase shifted by 90° so that the visibility seen by the detector at the output of the interferometer is maximized.

In the first setup (Pockels cell inside the interferometer), the quantum erasing analyzer should be set at the angle θ, such that $\tan\theta=\varepsilon/T^{0.5}$, where $\varepsilon=[(E_0*T^2)/(2^{0.5}*k)]^{-1}$ (E_0 is the initial intensity entering the interferometer; T is the relative fluctuation of the beam exiting the external Pockels cell; and k is the intensity of the beam exiting the noise-eater.) In the second setup, if E_1 is the average intensity of the beam exiting the external Pockels cell, and k is the intensity of the beam exiting the noise-eater, $\tan\theta=E_1/(2k)$.



I have learned a tremendous amount of physics and gained very much experience in experimental science this semester. There were many unexpected subtleties and difficulties encountered in the process of doing my project. The noise-eater's response to input modulations has been shown to be within specification for its operable bandwidth, particularly from 10kHz upwards. Noise reduction for higher frequencies is more relevant to the ion addressing system because the laser π–pulses will be shorter than 0.1ms. Given that the variable phase-changing properties of the noise-eater have already been predicted, all that remains is to collect test data. Upon complete characterization of the noise-eater, it will be incorporated into the addressing system of the ion-trap experiment.